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LETTER

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Mapping global human dependence on marine ecosystems

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Abstract

Many human populations are dependent on marine ecosystems for a range of benefits, but we understand little about where and to what degree people rely on these ecosystem services. We created a new conceptual model to map the degree of human dependence on marine ecosystems based on the magnitude of the benefit, susceptibility of people to a loss of that benefit, and the availability of alternatives. We focused on mapping nutritional, economic, and coastal protection dependence, but our model is repeatable, scalable, applicable to other ecosystems, and designed to incorporate additional services and data. Here we show that dependence was highest for Pacific and Indian Ocean island nations and several West African countries. More than 775 million people live in areas with relatively high dependence scores.

By identifying where and how people are dependent on marine ecosystems, our framework can be used to design more effective large-scale management and policy interventions.

KEYWORDS
coastal protection, ecosystem services, food security, human dependence, ocean management, sustainable development

1 | INTRODUCTION

The value of living natural resources to human well-being is becoming increasingly well-recognized, including the importance of marine ecosystems to people (Arkema, Verutes, & Wood, 2015; FAO, 2016; Hall, Hilborn, Andrew, & Allison, 2013; Millennium Ecosystem Assessment, 2005). Coastal and inland populations derive a range of monetary and non-monetary benefits from marine ecosystems including nutritional, economic, cultural, and coastal protection benefits. For example, marine fisheries are a critical source of lipids and micronutrients (Kawarazuka & Bene, 2010), support more than 260 million livelihoods (Teh & Sumaila, 2013), generate sizeable revenues for many countries, including US$ 80 billion dollars in export revenues for developing countries (FAO, 2016), and provide substantial coastal protection services with coral reefs reducing wave heights by up to 70% (Narayan, Beck, & Reguero, 2016).

Although these numbers provide a snapshot of the magnitude of benefits that living marine resources (hereafter marine resources) can provide, they offer only limited guidance on the ways in which people are dependent and how that dependence varies spatially. This knowledge gap poses challenges for regional and national policymakers as well as funders, who risk ignoring or underestimating the importance of marine ecosystems in policy efforts and large-scale management planning. To make more effective policy and management decisions, we need a conceptual understanding of dependence and a quantitative estimate of how and where people depend on natural ecosystems for their well-being.

Prominent recent initiatives highlight the importance of integrating sustainable development and resource use into environmental management, including the United Nations Sustainable Development Goals (SDGs) (Sustainable Development Platform, 2014). Sustainable management of marine resources is important for several SDGs including those related to poverty (goal 1), hunger (goal 2), health (goal 3), economic growth (goal 8), and climate-related disaster risk reduction (goal 13), and sustainable ocean management (goal 14) (Sustainable Development Platform, 2014). Understanding patterns of human dependence on marine resources is necessary for achieving these goals and for improving human well-being through better resource management. In order to design policies and management that meet multiple SDGs, decision-makers need to understand the mechanisms that create dependence.

In a first attempt to provide such information, we designed a novel quantitative framework for assessing dependence that is spatially scalable, repeatable, and applicable across different ecosystems. Our framework is also capable of incorporating additional indicators or ecosystem service dependencies. We applied our framework globally to assess three different types of dependence on marine resources—nutritional, economic, and coastal protection—using global, publicly available indicators (Table 1; Figure 1). Our focus is on assessing the relative degree of dependence, but we also estimate where the greatest concentrations of highly dependent people are located. Our results illustrate where people are relatively more dependent on marine resources and for what key benefits, so that policies and large-scale planning can be designed more effectively.

2 | METHODS

2.1 | Degree of dependence

Using expert input, we identified four key types of dependence on marine resources: nutritional, economic, coastal protection, and cultural (Supporting Methods; Table 1). Marine ecosystems are key to cultural identity and well-being (Russell, Guerry, & Balvanera, 2013), but we lacked global indicators to include it.

Original data resolution varied by data source, but all calculations were done on a 0.167 decimal degree grid (~17 km at the equator) to preserve some of the underlying spatial variability in the datasets. For nutritional and economic dependence, we take the mean of all grid cell values within a country and report our results at the national scale because most data were at that scale (Table S1). Data for coastal protection were largely at finer scales so coastal protection maps reflect the 0.167 decimal degree grid scale (Figure 1). For each type of dependence and mechanism, we chose relevant indicators (Table 1), transformed them to meet assumptions of normality, and standardized them [0-1] (Supporting Methods; Table S3).

TABLE 1 Indicator descriptions, their conceptual links to the three mechanisms underpinning the different types of dependence, and the sources that support those links. See Table S1 for information on data resolution, year, and data source

Type of dependence	Mechanism	Global proxy indicator(s)	Indicator description	Source for conceptual link
Nutrition $a * \frac{(b+(1-\overline{(cd} * 0.5e))}{2}$	Magnitude of benefit	Percentage of marine dietary protein to animal protein (*a*)	Measure of the amount of marine protein in animal protein intake, a proxy for the consumption of micronutrients. Higher values indicate greater benefit.	(Kawarazuka & Bene, 2010)
	Susceptibility	Percentage of underweight children under 5 (*b*)	Measure of food utilization, where higher values indicate greater susceptibility.	(FAO et al., 2015)
	Substitutability	Dietary diversity for protein (*c*) and fat (*d*), gross domestic product (GDP) (*e*)	Measure of the availability of alternatives for protein and fat and financial resources to purchase them. Higher values indicate greater substitutability.	(FAO et al. 2015; Kawarazuka & Bene, 2010)
Economic *Total*: $\overline{fg} * \frac{(\overline{hi}+(1-\overline{jkl}))}{2}$ *Revenue only*: $\bar{f} * \frac{(\bar{h}+(1-\overline{jkl}))}{2}$ *Jobs only*: $\bar{g} * \frac{(\bar{i}+(1-\overline{jkl}))}{2}$	Magnitude of benefit	% of GDP from fisheries revenue and public fishing access agreements (*f*), % of fisheries jobs to total jobs (*g*)	Measures of the proportional benefit provided by fisheries (based on exports and fishing access agreements) to national revenue and the number of jobs to national employment. Higher values indicate greater benefit.	(Allison et al., 2009)
	Susceptibility	GDP trend (*h*), Unemployment rate (*i*)	Measure of macroeconomic and microeconomic stability, where negative trends indicate more susceptibility to fisheries revenue and job losses.	(Allison et al., 2009; Mavragani et al., 2016)
	Substitutability	GDP (*j*), Education (*k*), Governance (*l*)	Measures of the financial resources available, ability to obtain other employment, or to address issues in the fisheries sector (e.g., retraining). Higher values indicate higher substitutability.	(Allison et al., 2009; Mavragani et al., 2016)
Coastal protection $m * \frac{(n+(1-\overline{opq}))}{2}$	Magnitude of benefit	Exposure (*m*)	Measure of the benefit to human populations (proportion of population, scaled nationally) from coral reefs and mangroves in reducing exposure from storms and sea-level rise. Higher values indicate greater benefit.	(Arkema et al., 2013)
	Susceptibility	Low elevation coastal zone (LECZ) population (*n*)	Measure of the proportion of the population susceptible to storms and sea-level rise. Higher values indicate more people are susceptible.	(McGranahan et al., 2007)
	Substitutability	GDP (*o*), Governance (*p*), Density of impervious surfaces (*q*)	Measure of people's ability to purchase substitutes (e.g., storm defenses), institutional capacity for disaster preparedness, and infrastructure for dealing with flooding. Higher values indicate greater substitutability.	(Adger et al., 2005; Brooks et al., 2005; Tol et al., 2004)

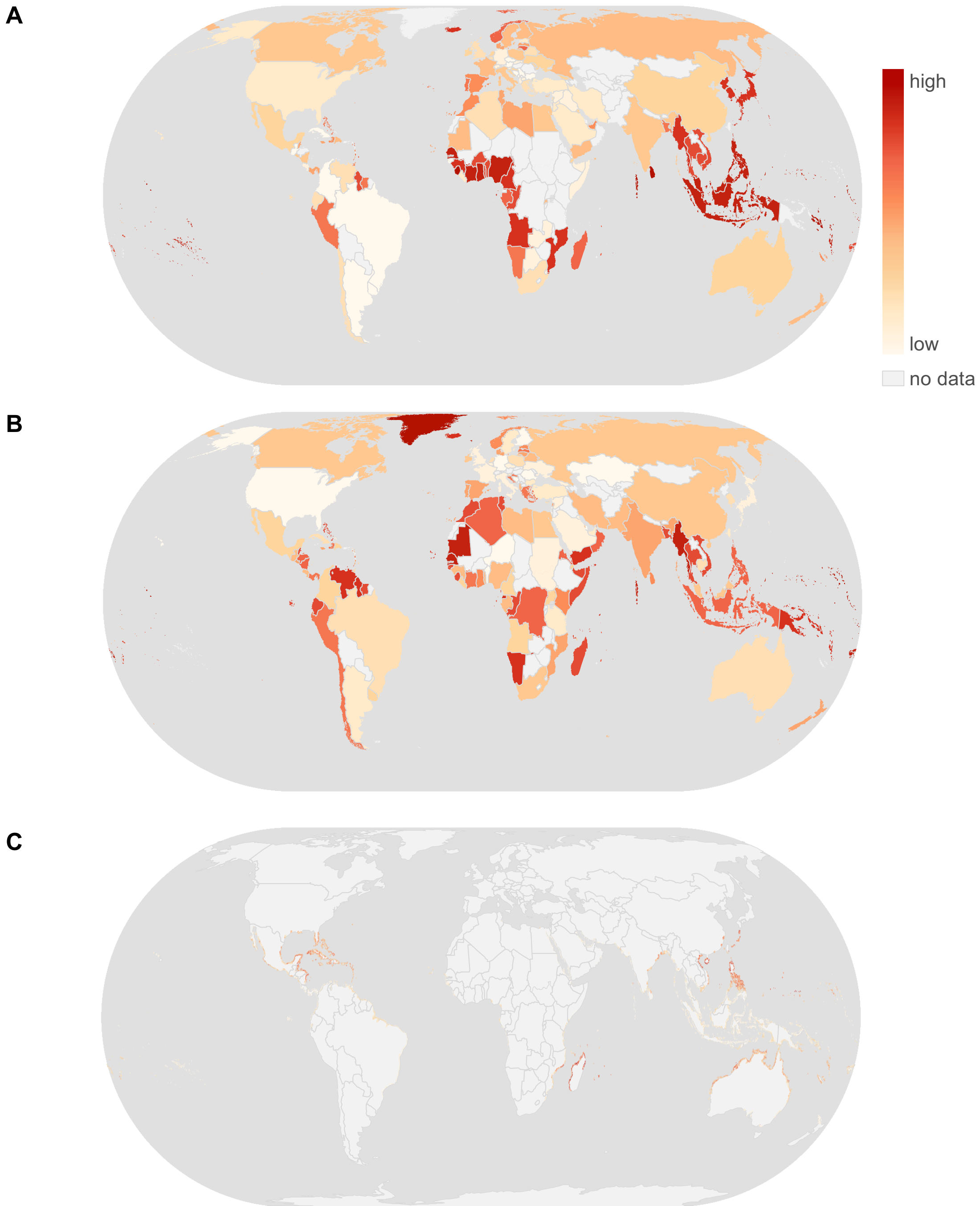

FIGURE 1 Degree of human dependence on marine ecosystems for (A) nutritional, (B) economic (fisheries), and (C) coastal protection dependence

2.2 | Population analyses

We also identified where the greatest concentrations of people that have relatively high dependence are located. First, we focused our analysis on regions that were within 200 miles of the coastline (Bright, Coleman, Rose, & Urban, 2012), where dependence on marine ecosystems is likely more direct. Then we excluded areas that had a density less than 1 person per kilometer grid cell. Within these coastal regions, we identified places where the dependence value was in the top 10% of values for one of the three dependence types. Then we calculated the number of people living in these regions of relatively high dependence (Bright et al., 2012).

2.3 | Robustness analyses

Composite indices are artificial constructs and as such require an analysis of their robustness to different construction algorithms (Saisana, Saltelli, & Tarantola, 2005). For the calculation of each dependence type, we standardized indicators [0-1] to ensure that indicators with larger ranges did not have greater importance in the analysis. We then calculated robustness metrics to determine whether our results were robust to different standardization methods (min-max, z-score, deviation from the mean) and different aggregation approaches (workshop-defined formula, arithmetic mean, geometric mean) that were used to combine indicators to calculate each dependence type (Table 1) (OECD and European Commission's Joint Research Center 2008; Supporting Methods). To calculate integrated dependence (mean across dependence types), we weighted each dependence type equally.

3 | RESULTS

3.1 | Human dependence framework

We developed an overall conceptual framework to quantify nutritional, economic, and coastal protection dependence on marine ecosystems (Supporting Methods; Table 1). This quantitative framework is based on three key mechanisms: the magnitude of the benefit of the ecosystem service, the susceptibility of the human population to a loss of that benefit, and the level of substitutability of that benefit (Table 1). For each mechanism and type of dependence, we then identified indicators that have a conceptual link established in previous studies for quantifying that mechanism (Table 1). The general form of the framework is:

$$\text{Dependence} = B \times \left(\frac{\bar{C} + \left(1 - \bar{S}\right)}{2} \right), \tag{1}$$

where B is the magnitude of the ecosystem benefit of the service, $\bar{C}$ is the mean of the susceptibility indicators, and $\bar{S}$ is the mean of the substitutability indicators. The magnitude of the ecosystem benefit (hereafter, benefit) of the service is defined as the "current" (based on most recently available data), realized benefit from an ecosystem service (Balmford, Fisher, & Green, 2011). This definition does not account for sustainability, so current levels of dependence may not be met in the future if demand exceeds supply. By focusing on realized benefits, we also implicitly account for cases where there may be greater supply, but less demand. Substitutability was broadly defined as a function of the quantity and diversity of alternatives and their accessibility, including having the financial resources to obtain or build alternatives. Greater substitutability will generally mean less dependence, so we take the inverse for all substitutability indicators. We chose a linear function because there is no evidence that these factors would have an exponential relationship. In our framework, dependence results from the multiplicative relationship between the magnitude of benefit of the service (B) and susceptibility (C) and substitutability (S) because the factors interact with each other. Because dependence is based on a realized ecosystem benefit and the indicators for susceptibility and substitutability are based on vulnerability to a loss of that specific benefit, we do not calculate dependence when B is absent or zero. If a susceptibility (C) and substitutability (S) indicator is absent, we take the mean of the available indicators. The relationship between susceptibility (C) and substitutability (B) is additive because they can compensate for each other to some extent. If substitutability is high, the population may be less susceptible to a loss of the service because an alternative is available. We did not apply any weighting because there is currently no conceptual evidence to support it. The form of the calculation for each type of dependence followed Equation (1), but varied slightly (Table 1). We find our results are robust to different standardization-aggregation approaches (Supporting Results).

3.2 | Dependence patterns

Pacific and Indian Ocean island nations, several countries along the west coast of Africa, and some countries in Southeast Asia ranked highest for nutritional and economic dependence (Figure 1A,B; Table S6). Although nutritional and economic dependence were relatively correlated (Pearson correlation coefficient = 0.58; $P < 0.0001$), several countries exhibited high dependence by one measure, but not the other (Figures 1A,B and S8). When economic dependence was disaggregated, dependence on jobs versus revenue also showed modest correlation (Figures 2 and S9; Table S6; Pearson correlation coefficient = 0.64, $P < 0.0001$). Coastal protection showed relatively distinct patterns from both nutritional (Pearson correlation coefficient = −0.07; $P < 0.51$) and economic dependence (Pearson correlation coefficient = −0.12; $P < 0.21$), with the highest values along cyclone-prone coasts (Figure 1C). When data for all three types of dependence were available (40% of countries), countries with highest mean dependence were Kiribati, the Maldives, and Tuvalu (Figure 3, Table S6). Across all countries, Kiribati also had the highest cumulative (total value across all types of dependence) dependence (Figure S10).

Country rankings changed significantly when we calculated where the greatest numbers of people with relatively high dependence were located (Tables 2 and S7–S10). Globally, more than 775 million people were in the top 10% of one of the dependence types (Table 2).

4 | DISCUSSION

Understanding where and how people are most dependent on marine resources is essential to helping guide improved large-scale management, prioritize investments, and inform policies

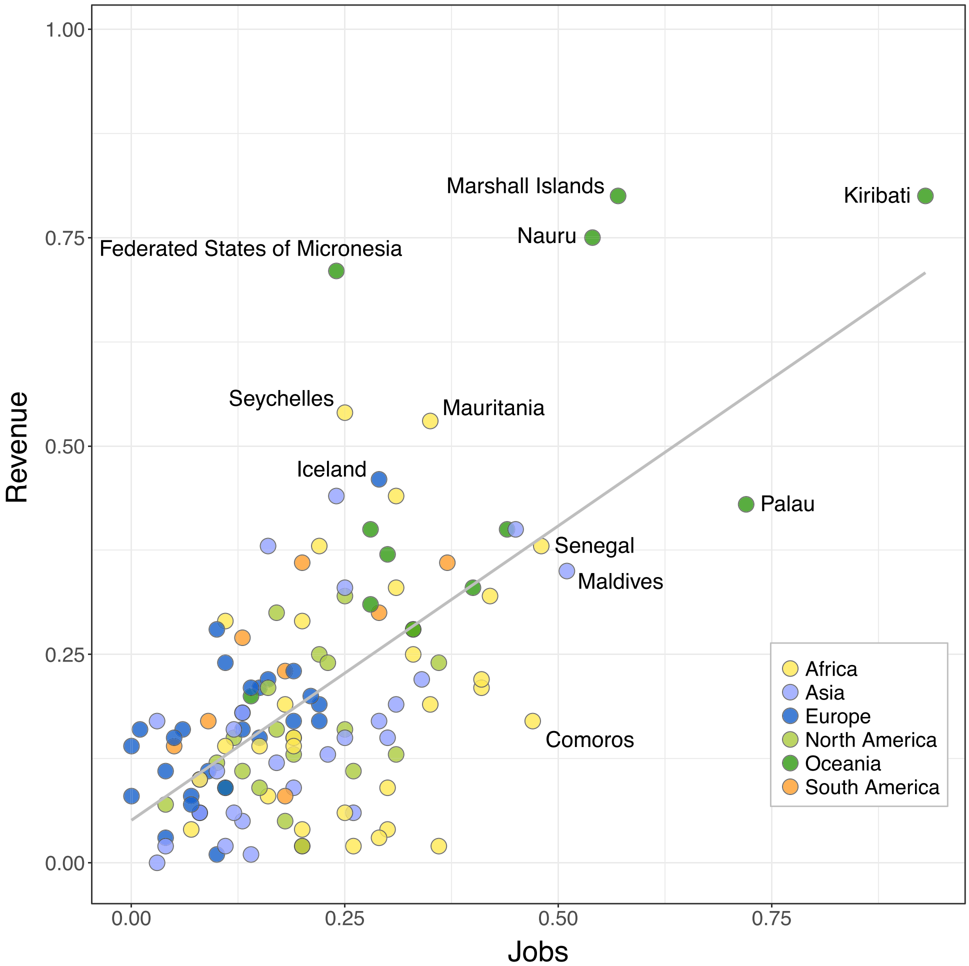

FIGURE 2 Relationship between dependence on fisheries jobs and dependence on fisheries revenue (both components of economic dependence on fisheries)

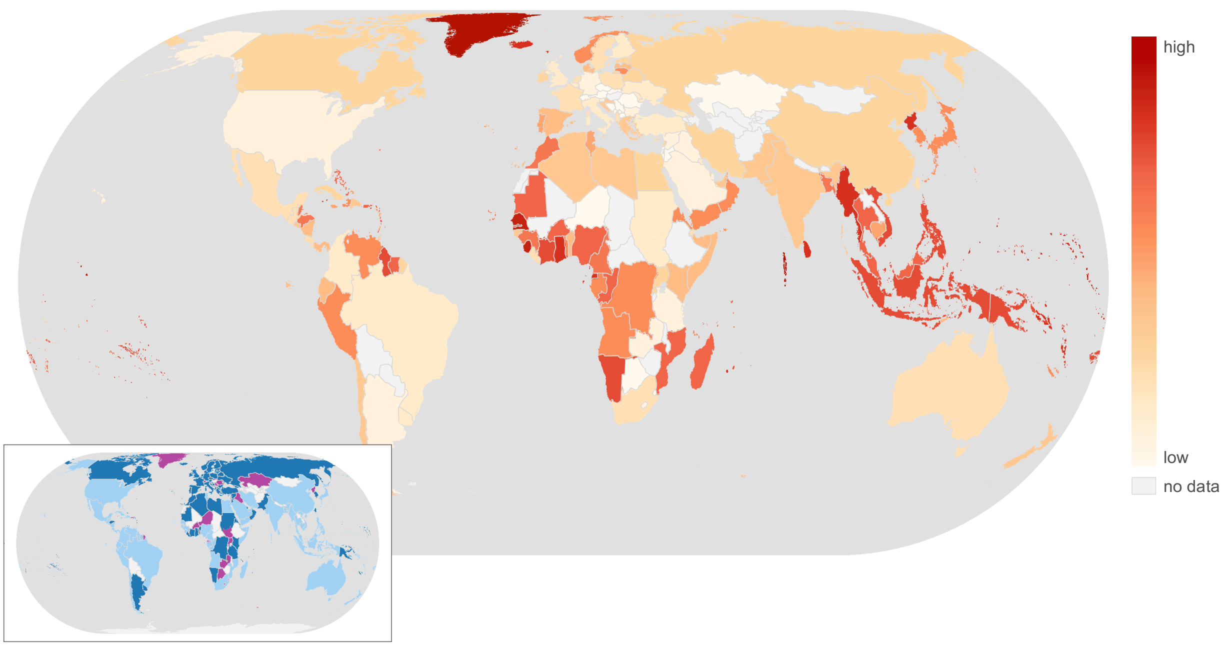

FIGURE 3 Integrated human dependence on marine ecosystems and number of types of dependence calculated (inset). The integrated map is the mean of nutritional, economic (fisheries), and coastal protection dependence scores. In the inset, the number of dependence types used for the calculations is shown (purple = 1, blue = 2, and light blue = 3 types)

TABLE 2 Top 5 countries with the greatest numbers of people with high dependence (top 10% of values for one of the dependencies) in descending order. See Tables S7–S10 for population numbers for all countries

Country rank	Nutritional	Economic	Coastal protection	All dependencies
1	Indonesia	Myanmar	Philippines	Indonesia
2	Philippines	Vietnam	China	Philippines
3	Nigeria	Morocco	Vietnam	Nigeria
4	Malaysia	Venezuela	India	Vietnam
5	Ghana	Yemen	United States	Myanmar
Dependent population (Top five countries)	**444,589,000**	**163,015,000**	**65,562,000**	**479,104,000**
Dependent population (all countries)	**524,514,000**	**240,734,000**	**76,559,000**	**775,308,000**

and planning processes that maintain the essential benefits people rely on. Our results highlight countries where societies and economies are dependent on ecosystem benefits from coastal and marine ecosystems. Patterns varied by country and type of dependence, but many island nations in the Pacific and Indian Oceans had high levels of dependence (Figure 1) whereas countries like Indonesia and the Philippines had greater concentrations of people with relatively high dependence (Table 2). By identifying which types of dependence are important and the mechanisms underlying them, policy can be better tailored to meet the needs of these populations.

4.1 | Mechanisms of dependence

We found nutritional dependence to be highest in West Africa and in several Pacific and Indian Ocean island nations, although scores were also relatively high for some developed countries (Figure 1A; Table S6). Drivers of high scores varied by the mechanism underpinning the dependence (Table 1). High dependence scores in Pacific and Indian Ocean island nations and several developed countries (e.g., Norway, Iceland, and Japan) were driven by high fish consumption rates (i.e., high magnitude of benefit) or a strong cultural preference for fish. By contrast, high dependence in West African countries was driven by different mechanisms, principally high susceptibility (i.e., the percentage of underweight children) combined with low substitutability (low dietary diversity and low GDP) (Figures S1B–D and S1j). These results not only highlight where human populations are dependent on marine resources for their nutrition, but also how the mechanisms that contribute to this dependence vary in different geographies.

Economic dependence patterns varied depending on the relative importance of jobs or revenues in different countries (Figures 2 and S9). Countries with high dependence on revenue from fisheries exports or foreign fishing access agreements were generally those with major pelagic fisheries or high value fisheries like tuna (Figure 2; Table 3). High dependence for jobs was more common in countries with sizeable small-scale fisheries (Teh & Sumaila, 2013). Future analyses could assess fishing effort by foreign vessel fleets, the EEZs targeted by those fleets (Pauly & Zeller, 2016), export data on volume (FAO, 2014), and fish price databases (Tai, Cashion, Lam, Swartz, & Sumaila, 2017) to better understand how international harvesting patterns and trade may affect economic dependence.

Results for coastal protection dependence showed relatively distinct patterns from both nutritional and economic dependence (Figure 1C). In our analyses, high coastal protection dependence arises from a combination of high cyclonic storm frequency as well as the presence of key habitats−coral reefs and mangroves−that protect coastal areas (Table 1). We could not completely account for impacts from low frequency, but high severity storms such as those that may occur in Myanmar and Bangladesh (Figure S1l; Needham, Keim, & Sathiaraj, 2015). In addition, we underestimate dependence in temperate regions because we did not have data on non-cyclonic or extratropical storms or the extent of salt marshes, dune systems, and oyster reefs. Furthermore, various local-scale physical and ecological variables besides ecosystem presence will determine protective capacity (Arkema, Guannel, & Verutes, 2013). As more temperate ecosystem and exposure data become available, we can incorporate them into our framework to better assess global coastal protection dependence.

Analyzing patterns of mean dependence across available types of dependence highlights places where there are multiple, interacting benefits (Figures 3 and S10; Table S6). High dependence often also includes high susceptibility and low substitutability, which may indicate strong vulnerability to a loss of the benefits from marine resources. In places where there are multiple dependencies, policymakers must also consider how best to manage across them.

4.2 | Population concentrations of high dependence

Roughly, 775 million people were found to be relatively highly dependent on marine ecosystems (top 10% of values for one of the three type of dependence; Tables 2 and S7–S10). Of these, 525 million people were found to be relatively highly dependent on marine ecosystems for nutrition, illustrating

TABLE 3 **Linking dependence pathways to management and policy.** The dependence path describes the combination of dependence mechanism

Dependence	Dependence path	Management focus	Examples of high dependence countries	Management or policy considerations
Nutritional dependence	High benefit + high susceptibility + low substitutability	Food security	Maldives, Kiribati, Solomon Islands, Sierra Leone, Sri Lanka	Access for small-scale fishers; Manage fish stocks sustainably; Acknowledge role of seafood in nutrition policy; Reduce waste and improve food safety; Availability of seafood to vulnerable populations
	High benefit + low susceptibility + high substitutability	Food quality and diversity (cultural preference)	Japan, Iceland	Export and import trade policies
Economic	High benefit for *jobs and revenues* + high susceptibility + low substitutability	Overall economic gains from fisheries	Marshall Islands, Kiribati, Nauru	Manage fish stocks sustainably; Consider potential trade-offs between policies maximizing benefits for jobs or revenues
	High benefit for *jobs* + high susceptibility + low substitutability	Employment	Palau, Maldives, Senegal	Access for small-scale fishers; Support small-scale fisheries enterprises
	High benefit for *revenue* + high susceptibility + low substitutability	Revenue	Federated States of Micronesia, Seychelles, Mauritania	Manage fish stocks for profitability and economic efficiency; Reduce perverse subsidies, implement real cost recovery in fisheries access agreements
	High benefit for *revenue* + low susceptibility + high substitutability	Revenue	Iceland	Manage fish stocks sustainably; Consider how best to minimize trade-offs between fisheries and potential conflicts with other activities including energy development and mining
Coastal protection	High benefit + high susceptibility + low substitutability	Protection of coastal habitats	Madagascar, Mauritius	Protect or maintain coastal habitat integrity
	High benefit + high susceptibility + high substitutability	Green-gray infrastructure planning	Japan, China	Design grey infrastructure to be complementary to natural habitats; Protect or maintain coastal habitat integrity

the importance of marine fisheries to food security (Béné, Barange, & Subasinghe, 2015). More focus on these places may be needed, both in local management and in supply chains originating there, to ensure sustainable resource management and a continuation of these benefits in the face of increased human needs and pressures on marine resources.

4.3 | Linking people to ecosystems

Our quantitative model was designed to be scale-independent and flexible enough to incorporate improvements over time in the underlying datasets or the addition of more indicators (Table 1). We used global, publicly available datasets for our analysis (Table S1; Allison, 2011). For some indicators, we used proxies such as the percent of GDP from fisheries export revenues, because domestic fisheries revenue data were not available (Table 1). With finer-scale data, dependence could be calculated at more local, community-level scales.

All types of ecosystem benefits flow across space from ecosystems to people, but social, institutional, and knowledge mechanisms affect access to benefits (Hicks & Cinner, 2014). Many of the direct nutritional (e.g., fish caught) and economic benefits (e.g., fish processing) can be exported by communities or traded internationally (Swartz, Rashid Sumaila, Watson, & Pauly, 2010), making interventions for resource management and poverty reduction less clear (Béné, Arthur, & Norbury, 2016; Daw, Brown, Rosendo, & Pomeroy, 2011). Recent work has calculated spatial variation in estimates of the magnitude of some marine ecosystem services (Arkema et al., 2015). Our work identifies regions where communities are likely to be dependent on marine ecosystems services, which is a key step in linking people to the ecosystems that they depend on. More local-scale benefit transfer modeling and supply chain analyses would deepen our understanding of how and where specific ecosystems are providing benefits, the magnitude of those benefits and to whom they are accruing.

4.4 | Management and policy implications

Our results suggest that management may need to be customized according to which type of dependence is present if benefits are to be maintained (Allison 2011) (Table 3). By examining patterns in the types of dependence, policymakers can determine whether ecosystem health is primarily a concern for the safety of people and property in the coastal zone (coastal zone management and habitat protection policies), their nutrition and health (food, nutrition and public health policy) (Allison, Koehn, Franz, Wiegers, & Callens, 2017), their employment prospects (labor mobility and enterprise development, fishery management and development policies), or the role that an important sector of the maritime economy, like fisheries, plays in national economic development (fisheries management and trade policies) (Allison, 2011). Policy and management interventions can then be tailored to address the specific barriers to sustainable development (Table 3).

For example, countries with relatively high economic dependence associated with fisheries revenues like Mauritania may focus on consolidation and efficiency measures. Depending on the country, these could include reducing perverse subsidies (Arnason, Kelleher, & Willmann, 2008) or implementing real cost recovery (Le Manach, Chaboud, & Copeland, 2013) (Table 3). On the other hand, countries that rely on fisheries as a source of employment such as Senegal or Palau may want to focus on supporting small-scale enterprises (Allison, 2011) (Table 3). Indeed, fisheries management measures for revenue versus employment may also differ. Broadly, fishing mortality from fishing at open access equilibrium maximizes employment, whereas fishing mortality at Maximum Economic Yield maximizes macroeconomic benefits (Table 3). Policy measures could also aim to "diversify the dependence" by having a portfolio of fisheries that focus variously on exports, employment, or food security. With information on what drives dependence and how benefits are delivered, policymakers can try to develop policies and interventions that support the continued delivery of benefits from those services.

In developing management strategies, policymakers and managers must also consider that maximizing the delivery of one category of benefits may have trade-offs for the delivery of other benefits and the well-being of different groups (Daw, Coulthard, & Cheung, 2015). For example, a focus on the delivery of fish to local communities that are nutritionally dependent may result in less private investment in those fisheries as a commercial enterprise and less macroeconomic revenue (Allison, 2011; Bailey & Jentoft, 1990). On the other hand, there are potential "win-wins" for dependent communities such as the maintenance of coastal habitats like mangroves that serve both as nursery habitats for fisheries and providers of coastal protection services (Barbier et al., 2011). Maximizing synergies while minimizing trade-offs will require understanding the physical and ecological requirements needed to generate multiple benefits, their accessibility (Hicks & Cinner, 2014) and the full suite of potential trade-offs (Daw et al., 2015) to meet the needs of different, dependent beneficiaries.

A better understanding and representation of where and how people are dependent on marine ecosystems can help improve the integration of fisheries and marine ecosystems into discussions about sustainable development and poverty alleviation, particularly those focused on food security and livelihoods with the SDGs. Our novel conceptual framework provides an effective, streamlined approach for identifying dependent populations. Policymakers can then use this framework to design more effective development and resource management policies and practices to ensure that marine resources are sustainably managed for the benefits that are important to dependent populations.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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